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Performance analysis of water cooled concentrated photovoltaic (CPV) system

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ABSTRACT

The concentrated photovoltaic (CPV) system focuses solar radiation on the solar cells. CPV systems need to track the sun for keeping the reflected radiation focussed on the solar cell. A CPV module and its active water-cooling system are developed at the School of Energy and Environment, Southeast University, China and its performance has been reported here. This developed system has been used for testing the PV module's performance for different parameters such as operating temperature, power output, and efficiency. The experimental results show that the operating temperature of the CPV module under water cooling is reduced under 60 °C and therefore the efficiency of the CPV has increased and produced the more electric power output. The effect of water flow rate has been analyzed for the CPV efficiency and output.

Contents

1. Introduction

In developing countries, where rural electrification is embryonic, the applications of photovoltaic (PV) systems are important. Extending power lines from centralized sources to rural areas is often not yet economical, and so, decentralized power sources, such as the PV system, are a promising alternative [1]. Concentrated photovoltaic (CPV) systems concentrate solar radiation on the solar cells. CPV systems are required to track the solar radiation for keeping the reflected radiation focussed on solar cell. In CPV, lens or mirrors are used to concentrate solar radiation on solar cell. The main advantages of the CPV systems are high efficiency and relatively low system cost for getting more PV power output by using less expensive semiconducting PV material required for the same output. The CPV system can use reflective mirrors or lens to concentrate solar radiation on solar cell [2]. The effective solar radiation on the solar cell in the CPV systems is much more compare to flat solar cell and magnitude of effective solar radiation on CPV depends on the design of solar radiation reflector. The concentrated solar radiations also increase the solar cell operating temperature and due to that solar cell efficiency decreases and also the technical life time of the solar cell decreases [3]. For effective operation of the CPV, it is important to include the proper cooling system in the CPV systems. Solar cell cooling in CPV systems must be an integral part of the system to lower the cell temperature and hence improve the efficiency.

The common cooling methods for CPV are air cooling, water cooling, and heat pipe cooling [4]. The heat pipe cooling for CPV has been investigated in Ref. [5] for different working fluids and it also analyzed the fin sizes and their spacing for collecting the heat by natural convection from the CPV module with a total cell-to-ambient temperature rise of only 40 °C. Cooling of CPV for

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Nomenclature

A_m	aperture area of reflective mirrors (m^2)
G	intensity of solar radiation (W/m^2)
Q_u	heat output (W)
Q_e	electricity output (W)
$t_{w.i}$	inlet temperature of cooling water (°C)
$t_{w.o}$	inlet and outlet temperature of cooling water (°C)
m	mass flow rate of cooling water, (kg/s)
c_p	heat capacity of cooling water, (J/kg K)
I_m	maximum power point current (A)
V_m	maximum power point volatge (V)

polycrystalline silicon solar cells through heat pipes has been reported in Ref. [6] and compared the PV power output with and without heat pipe cooling and reported that output doubles under the heat pipe cooling with cell-to-ambient temperature rise of 46 °C. The single horizontal axis tracing parabolic trough type reflector has been introduced in the EUCLIDES project [7] for CPV and the fins have been used for cooling the solar cells. The aluminum fins size and separation have been reported in [7] and they have been done by using the heat transfer through air with simple conduction and convection models. Active air cooling of PV modules (without concentration) has been reported in Ref. [8] that the cell temperature can be reduced by 30 °C and hence the solar cell efficiency has improved. The comparison between the heat pipe cooling and water cooling on the performance of solar cell has been analyzed in Ref. [9]. The water cooling for the flat plate PV (without concentration) has been studied in Ref. [10] and it has been observed that the further performance of PV array can be improved through solar radiation concentration with water cooling. The Australian National University has developed a concentrating solar PV-thermal system by using the parabolic mirror and very encouraging results are reported: under typical operating conditions show thermal efficiency around 58% and electrical efficiency around 11%, therefore a combined efficiency of 69% [11]. The analysis of the above mentioned references show that CPV system based on proper water cooling can provide very good output with reduction in cell operating temperature and hence cell efficiency gets improved. A CPV test module and its active water-cooling system are developed at the Institute of Energy and Environment, Southeast University, China and its performance has been reported here. This developed system has been used for testing the PV module's performance for different parameters such as operating temperature, power output, and efficiency.

2. Experimental set-up

A CPV test device has been illustrated in Fig. 1. It includes solar cell module, water cooler, concentrator, machine frame, and transmission gear etc. The frame of reflective concentrator is located under the solar cells stand; the silver backed rectangle reflective mirrors are divided into two groups and installed at both sides of the frame symmetrically. There are six mirrors in every group and the mirrors focus the light onto the solar cell. The solar cell module and its stand, the reflective mirrors array and its frame are all installed at the mounting rack through the main shaft and the main shaft is connected with driver device. In this system, the main shaft and the mounting rack are controlled through the sunlight sensor and two-axis sun-tracing is carried out.

A mono-crystalline silicon solar cell module is used in this experiment. This solar cell is 1.08 m long and 0.14 m wide. The used aluminum water-cooler is shown in Fig. 2. The aluminum plate is 2.5 mm thick, the internal diameter of the pipe is 10 mm and the external diameter is 13 mm. The distance between the incoming and outgoing pipes is 70 mm and a flexible conduit is used to connect the two pipes. The water cooler is attached at the back of the solar cell module. At the same time, a fixed solar cell module, without concentration, is tested as for comparing the performance results. The fixed solar cell module is the same as the one used in CPV system. The fixed solar cell faces south and tilts at 35°. The E-type thermocouples are adopted to measure the temperature of cells. The main performance of solar cells including open circuit voltage, short circuit current, and the voltage and current at the maximum power point are measured with PVPM1000C solar cell tester which is produced by PV-Engineering GmbH Company, Germany. The ambient meteorological data have been measured by special meteorological data acquisition device. The cooling water is supplied by a pump and valve is used to regulate the water flow rate.

Fig. 1. Experimental set-up of water-cooled CPV module.

Fig. 2. Water cooling pipes of the CPV module.

3. Results and discussion

The electrical efficiency of the water-cooled CPV module is the ratio of the output electricity to the incident solar radiation and it is given by

$$\eta_e = \frac{Q_e}{A_m G} = \frac{I_m V_m}{A_m G} \quad (1)$$

The thermal efficiency of the water-cooled CPV module is defined as the ratio of the output heat to the incident solar radiation and it is given by

$$\eta_{th} = \frac{Q_u}{A_m G} = \frac{m c_p (t_{wo} - t_{wi})}{A_m G} \quad (2)$$

The solar intensity on the test day has been given in Fig. 3 and the peak solar intensity at solar noon was 1019 W/m^2. On the experiment day, the average wind speed was 0.25 m/s, the maximum wind speed was <1 m/s, the temperature of inlet water was between 31 °C and 32 °C. The hourly temperature of fixed solar cell, the concentration solar cell i.e. CPV and the ambient temperatures are shown in Fig. 4. The temperature of fixed solar cell and the temperature of the concentration solar cell have been reached to maximum at the solar noon time. The temperature of fixed solar cell was around 20 °C higher than the ambient temperature, and at the midday the difference was 23 °C. With decrease in solar radiation, the temperature of the fixed solar cell has been dropped and at the end of day the difference was 18 °C. During the test day, the maximum temperature difference between the concentration solar cell and the fixed solar cell was lower than 5 °C. The average temperature difference was approximately 3 °C and this temperature difference decreased after 14:30 pm. Compared with the fixed solar cell, the concentration solar cell module receives more illumination so more solar radiation transfer to heat and cause rise of the cell temperature. However, the experimental data has showed that the temperature difference between the concentration solar cell and the fixed solar cell is not very much. It has been observed that the cooling water extracts significant amount of heat gained from the temperature rise of the concentrated solar cell.

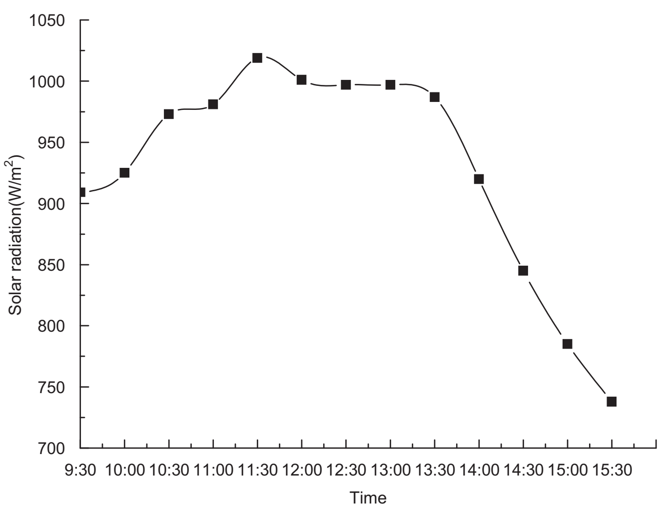

Fig. 3. Solar radiation with respect to day time.

The output electricity of the fixed solar cell and the concentration solar cell are given in Fig. 5. It has been found that the output electricity of the concentration solar cell is 4.7 to 5.2 times higher than the fixed cell. During the test day, the maximum produced electricity at solar noon from the concentration solar cell was 71.13 W, and from the fixed cell was 16.55 W. In this experiment, the concentrating ratio of the concentration solar cell was 8.5. The gain in the solar radiation and the output from the CPV can be increased significantly, but it was not achieved that much. The main reasons are the imperfection of concentrator geometry structure, the optic loss of the reflective mirrors and the efficiency drop due to the temperature rise of the solar cell. The PV cell output is in proportion to the cell short circuit current [12]. The effect of solar radiation concentration can be compared through the short circuit current of the concentration solar cell with that of the reference fixed solar cell. In Fig. 6, the effect of solar radiation concentration on solar cell with reference to the fixed flat solar cell has been given. The electrical efficiency, thermal efficiency of the CPV and the electrical efficiency of the fixed cell are shown in Fig. 7. It has been observed that at solar noon, the efficiency of both solar cells have lower values due to the higher cell temperature. At solar noon, the electrical efficiency of the CPV is 7.81% and of the fixed cell is 10.68%. After solar noon, the cell temperature has been decreased due to decrease in the incident solar radiation and therefore electrical efficiency of the solar cells has started increasing. It can also be observed by analyzing the Figs. 4 and 7. In the CPV, as the incident solar radiation has increased, so the solar cell temperature has also increased and therefore the cooling water has extracted more heat from the CPV module. Hence the thermal efficiency of the CPV has increased till noon and gradually decreased after the solar noon. The variation in the solar cell

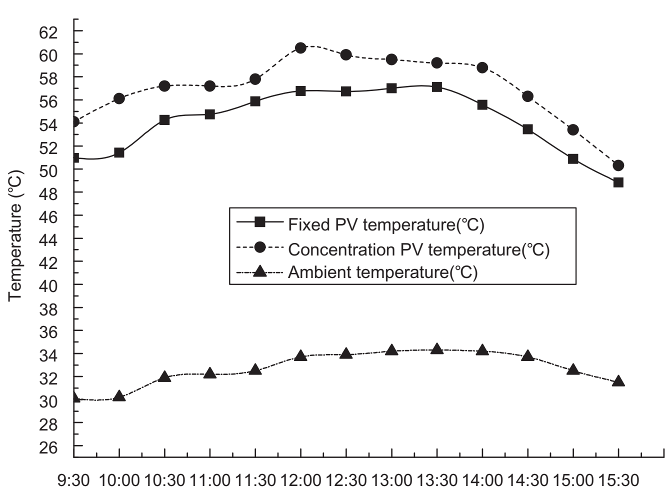

Fig. 4. Solar cell (CPV and flat) and ambient temperature with respect to day time.

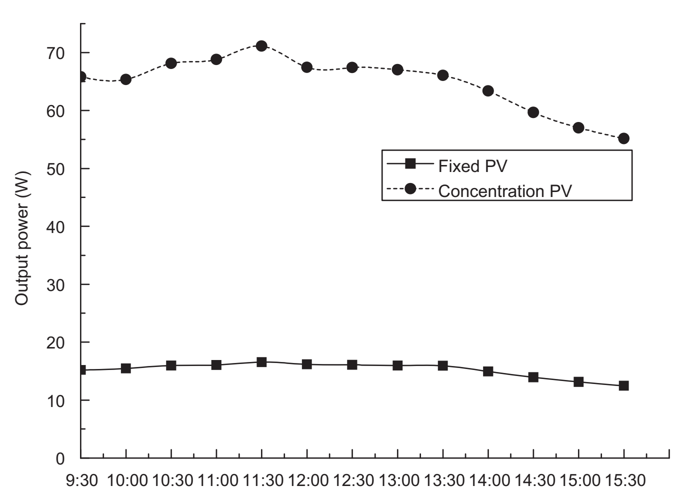

Fig. 5. PV modules output power.

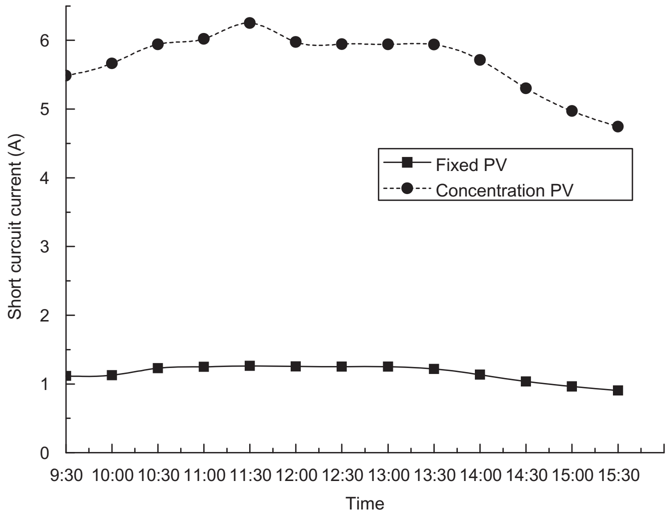

Fig. 6. Short-circuit current of PV modules.

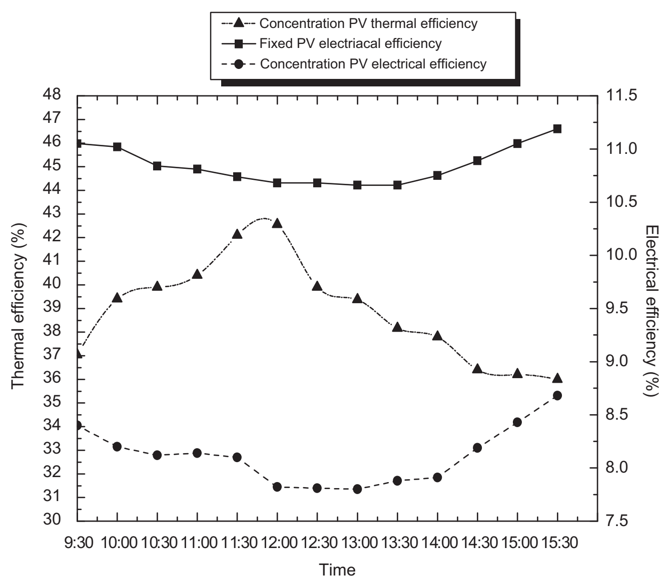

Fig. 7. PV modules electrical efficiency and thermal efficiency of CPV.

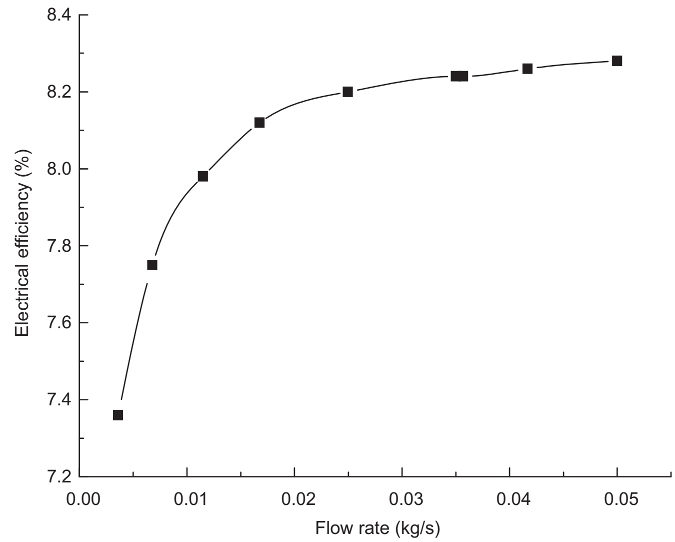

Fig. 8. Effect of water flow rate on electrical efficiency.

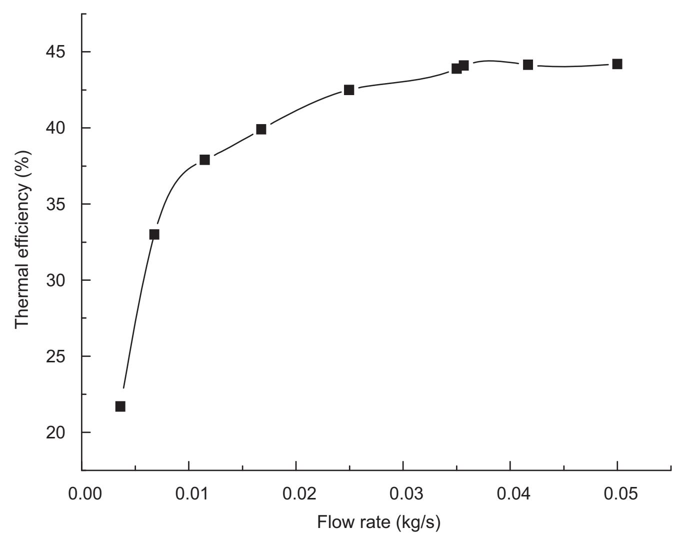

Fig. 9. Effect of water flow rate on thermal efficiency.

temperature and the heat extraction rates mainly depends on the incident direct solar radiation.

The effect of the cooling water flow rate on the electrical efficiency and the thermal efficiency of the CPV are given in Figs. 8 and 9. It has been observed that with increase in the cooling water flow rate, the electrical efficiency and the thermal efficiency increases rapidly and for the flow rate above 0.03 kg/s, the efficiency of the solar cell has become almost constant. As the water flow rate increases, the average temperature of the flowing water reduces. With the higher water flow rate, more heat is extracted from the solar cell and therefore the cell temperature decrease and the cell electrical efficiency increases. When the flow rate becomes more than a value (in this case i.e. 0.03 kg/s), the heat extracted by the cooling water reaches relatively at saturated level and therefore the efficiency of the solar cell remains relatively at constant level.

4. Conclusion

In this work, experimental performance analysis of a water-cooled CPV module has been presented. It has been observed that the performance of solar cell with cooling and concentration is much higher than the fixed solar cell under the same input conditions. It has been found that the output electricity of the concentration solar cell is 4.7 to 5.2 times higher than the fixed cell. During the test day, the maximum produced electricity at solar noon from the concentration solar cell was 71.13 W, and from the fixed cell was 16.55 W. In this experiment, the concentrating ratio of the concentration solar cell was 8.5. The gain in the solar radiation and the output from the CPV can be increased significantly, but it was not achieved that much. Based on the obtained experimental data, the output electricity of the concentration solar cell is around 4.9 times more than the fixed cell during the test day, but its electrical efficiency is lower than 9% at most of the time. The main reasons are the imperfection of concentrator geometry structure, the optical loss of the reflective mirrors, non-uniform illumination levels on the solar cell and the efficiency drop due to the temperature rise of the solar cell. With the higher water flow rate, more heat is extracted from the solar cell and therefore the cell temperature decrease and the cell electrical efficiency increases. The efficiency of the CPV mainly depends on the heat extraction rate which helps in managing the cell temperature and the heat extraction rate mainly depends on the cooling water flow rate.

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